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(54) **BANDWIDTH ALLOCATION OF BURSTY SIGNALS**

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H04L 12/26 (2006.01)

(52) **U.S. Cl.**
USPC **370/231**; 370/233; 370/234; 370/236; 370/237; 370/253; 370/395.21; 370/395.41; 370/395.42

(58) **Field of Classification Search**
USPC 370/252, 253, 229–237, 395.41, 370/395.21, 395.42
See application file for complete search history.

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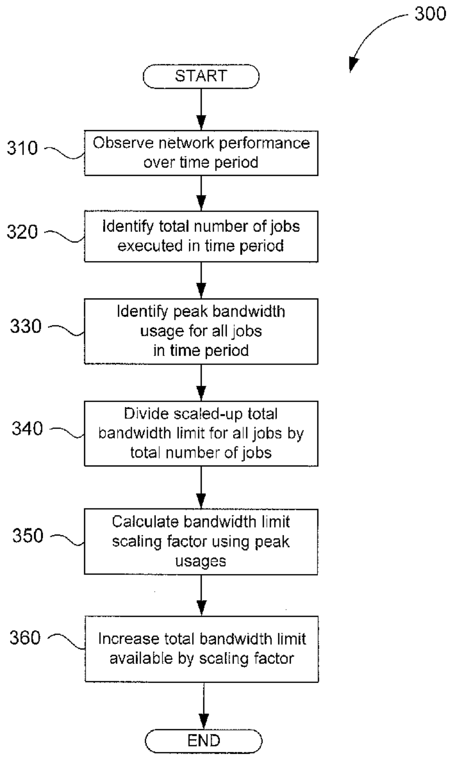
(57) **ABSTRACT**

Bandwidth is allocated by leveraging a bursty characteristic of data transmission signals to efficiently utilize network resources. Network performance is observed over a time period to identify patterns of data transmission rates as different signals are processed. To compensate for the fact that different jobs/tasks peak at different times, the total bandwidth limit may be increased by a scaling factor. The scaling factor is calculated using information obtained by observing network performance during the time period. The scaling factor is used to increase the total bandwidth available for all jobs/tasks executing during the time period without exceeding any bandwidth limits. The data transmission rate of each job/task may then be adjusted to utilize the newly available bandwidth.

18 Claims, 7 Drawing Sheets


300
START
310
Observe network performance over time period
320
Identify total number of jobs executed in time period
330
Identify peak bandwidth usage for all jobs in time period
340
Divide scaled-up total bandwidth limit for all jobs by total number of jobs
350
Calculate bandwidth limit scaling factor using peak usages
360
Increase total bandwidth limit available by scaling factor
END

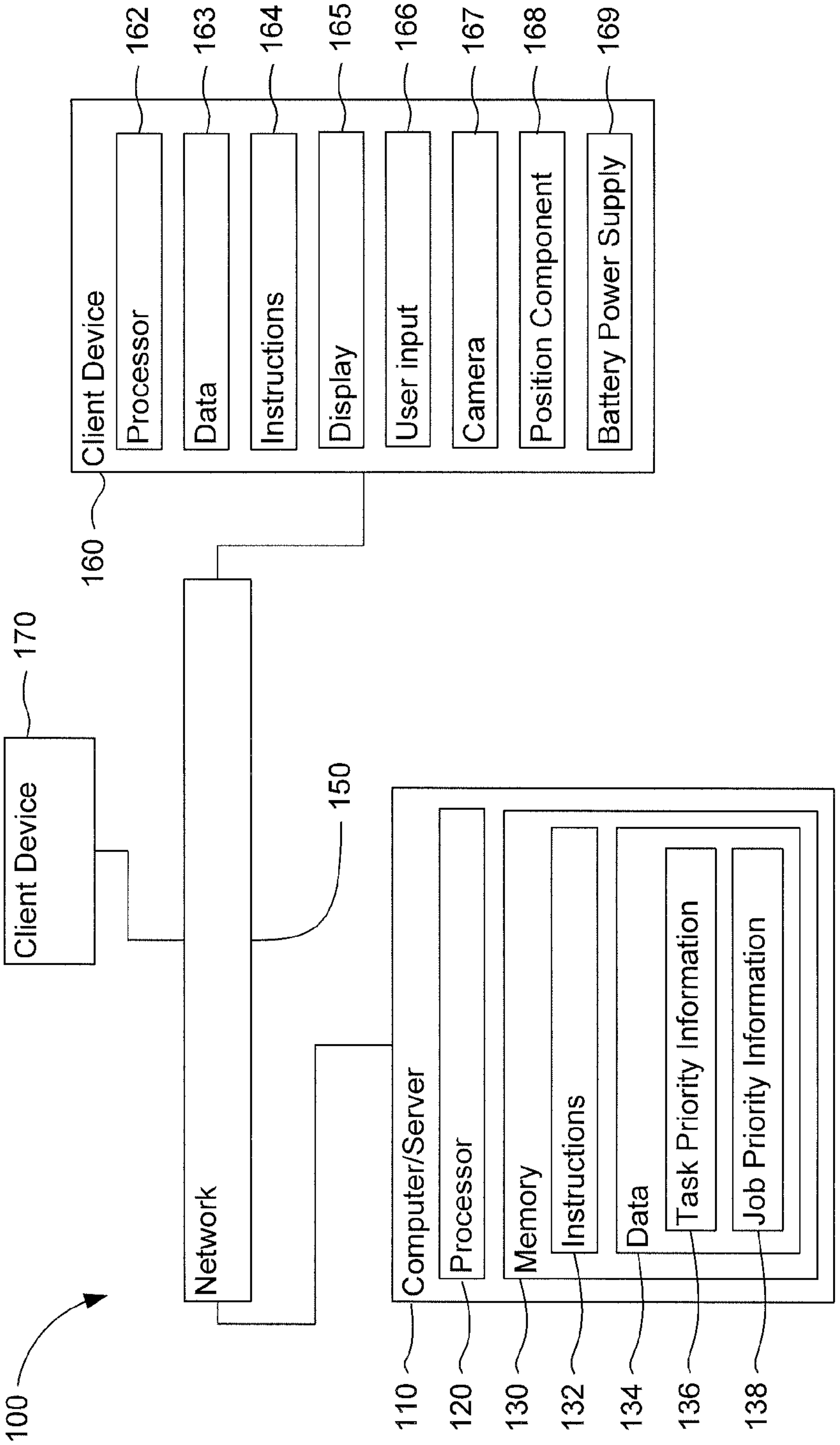

100
Client Device
170
Network
150
160
Client Device
162
Processor
163
Data
164
Instructions
165
Display
166
User input
167
Camera
168
Position Component
169
Battery Power Supply
Computer/Server
110
Processor
120
Memory
130
Instructions
132
Data
134
Task Priority Information
136
Job Priority Information
138

FIGURE 1

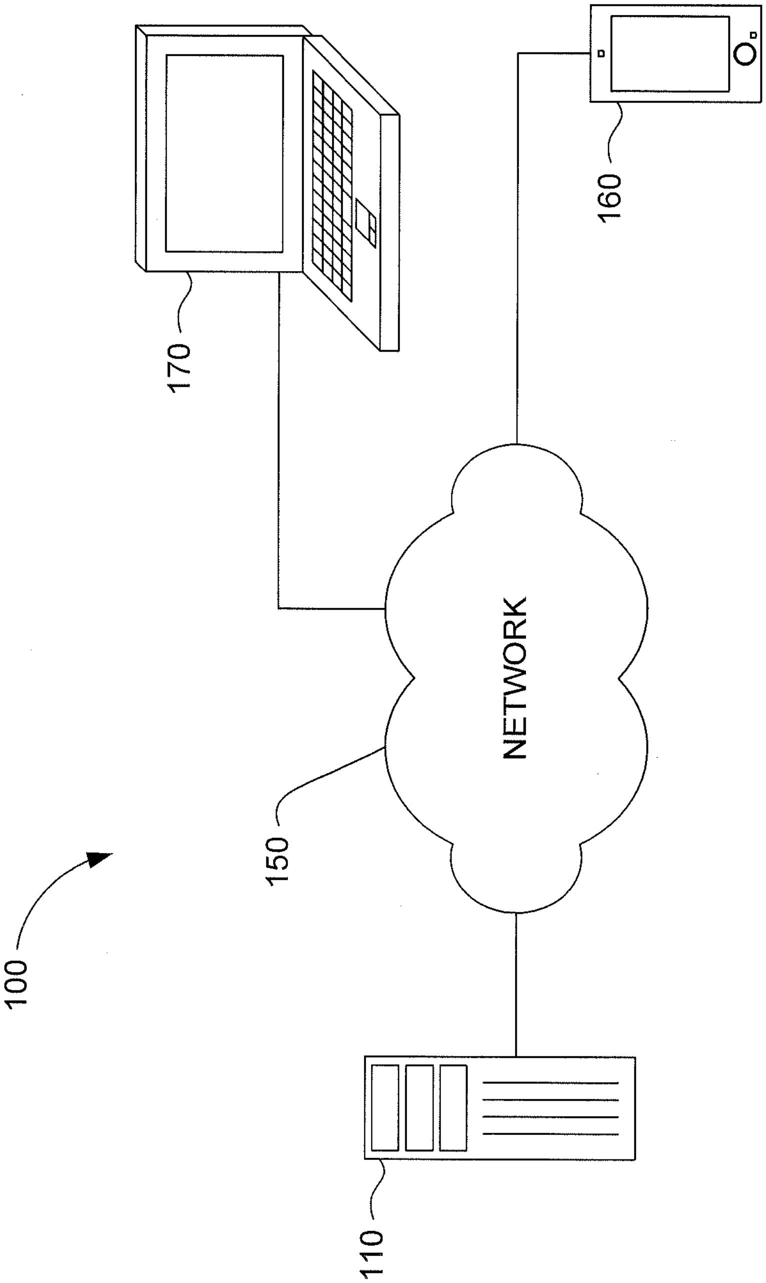


FIGURE 2

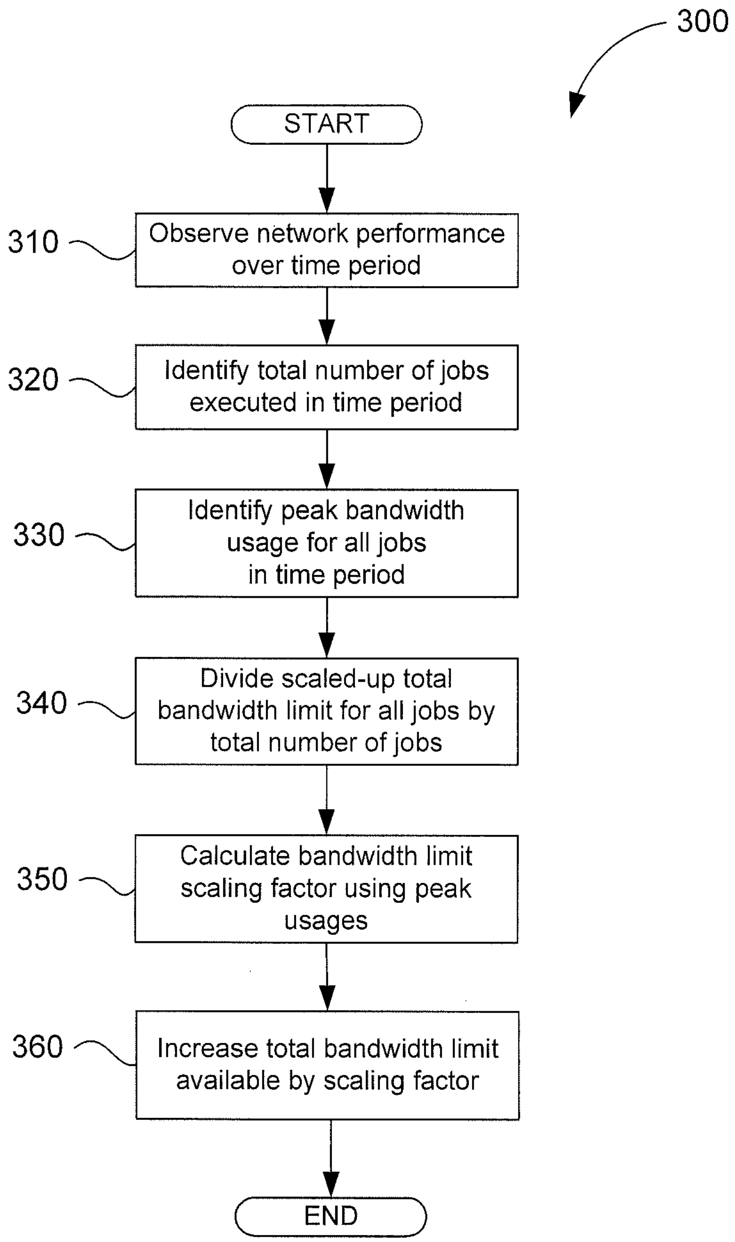

300
START
310
Observe network performance over time period
320
Identify total number of jobs executed in time period
330
Identify peak bandwidth usage for all jobs in time period
340
Divide scaled-up total bandwidth limit for all jobs by total number of jobs
350
Calculate bandwidth limit scaling factor using peak usages
360
Increase total bandwidth limit available by scaling factor
END

FIGURE 3

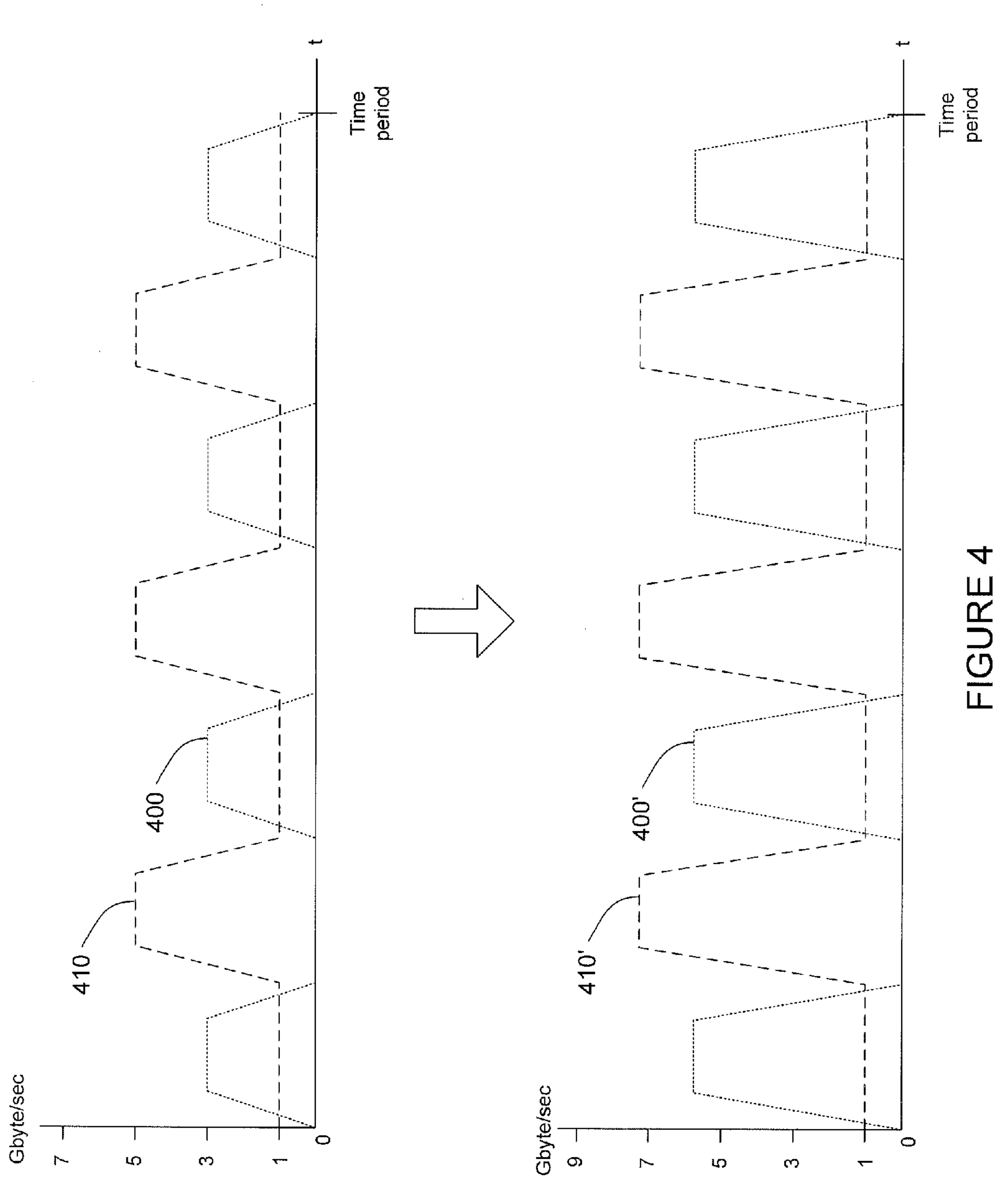

Gbyte/sec
7
5
3
1
0
410
400
Time period
t
Gbyte/sec
9
7
5
3
1
0
410'
400'
Time period
t

FIGURE 4

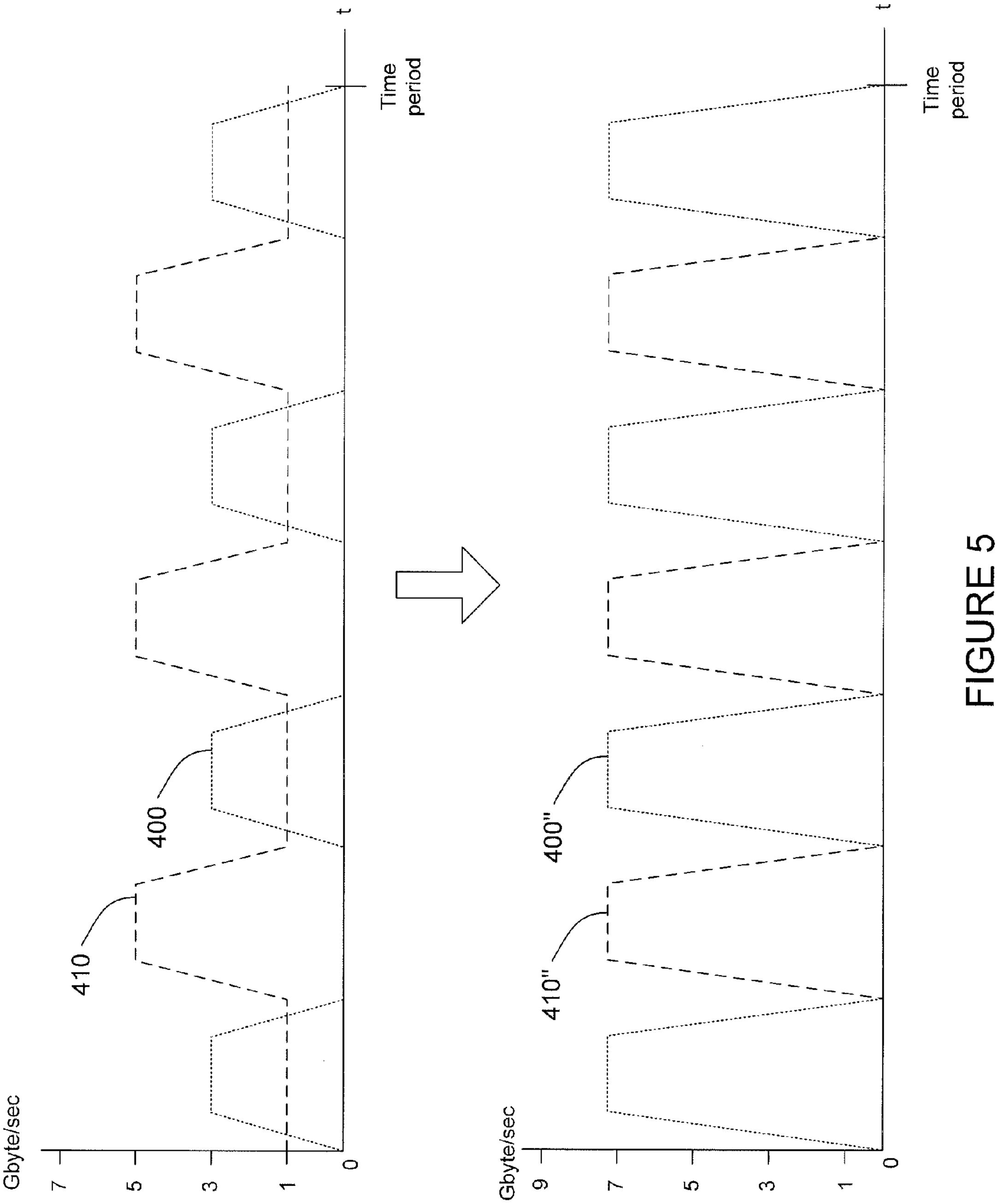

Gbyte/sec
7
5
3
1
0
t
Time period
410
400
Gbyte/sec
9
7
5
3
1
0
t
Time period
410"
400"

FIGURE 5

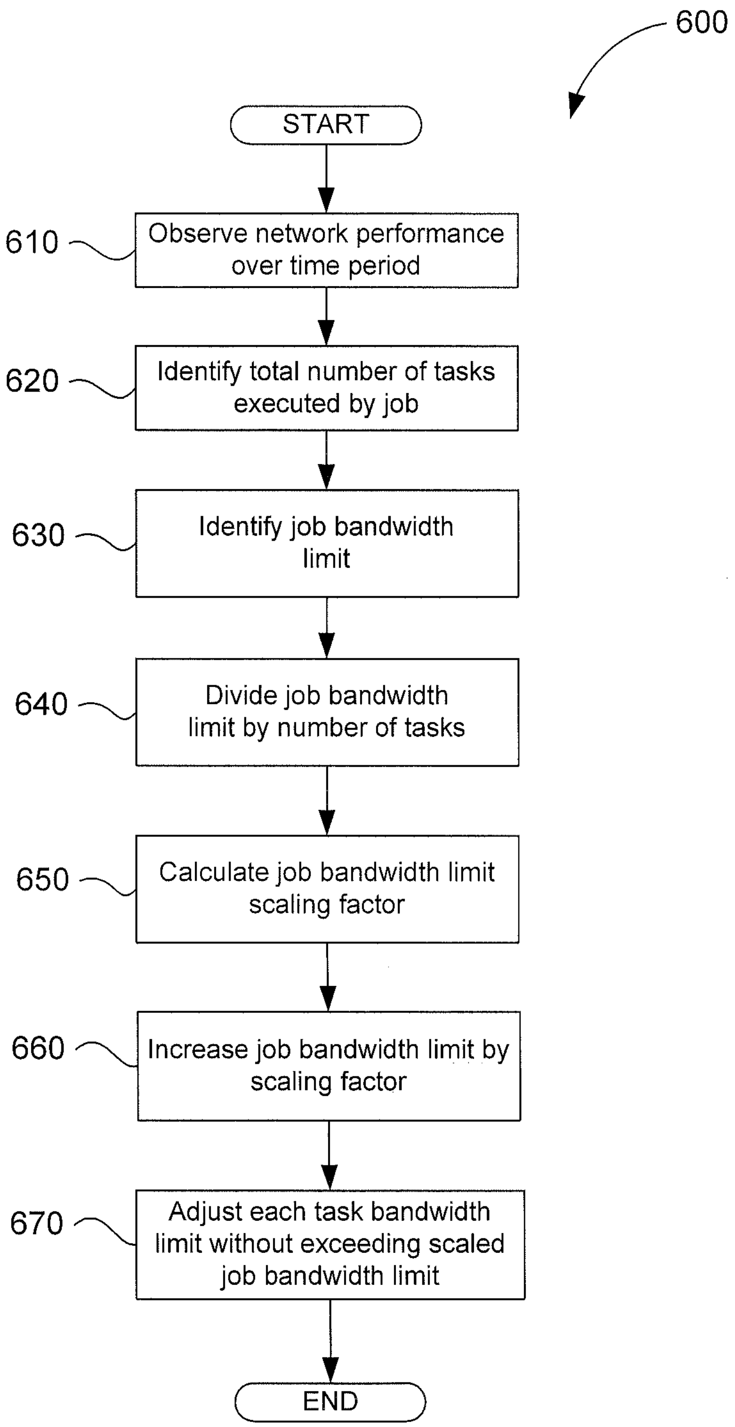

600
START
610
Observe network performance over time period
620
Identify total number of tasks executed by job
630
Identify job bandwidth limit
640
Divide job bandwidth limit by number of tasks
650
Calculate job bandwidth limit scaling factor
660
Increase job bandwidth limit by scaling factor
670
Adjust each task bandwidth limit without exceeding scaled job bandwidth limit
END

FIGURE 6

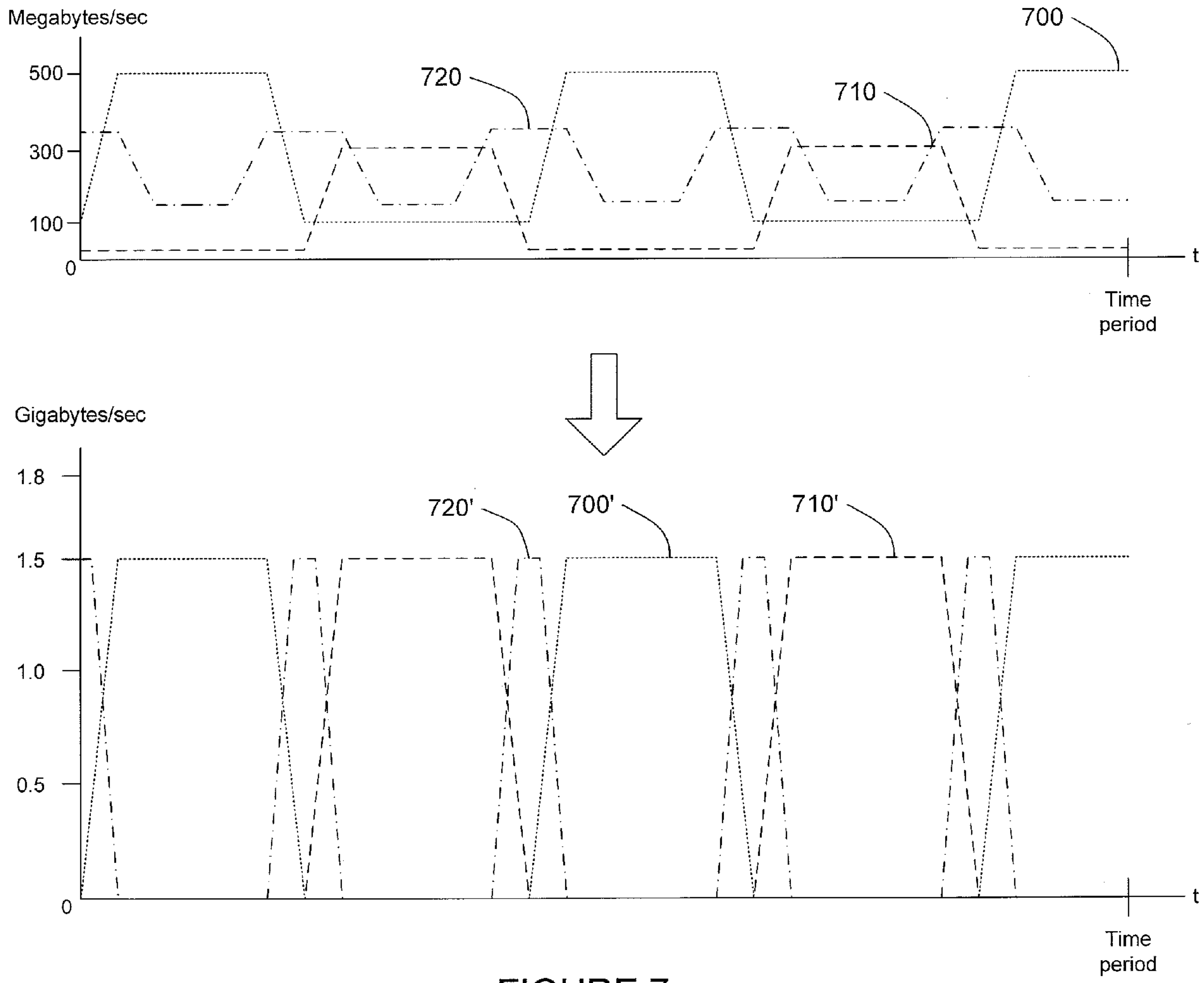

Megabytes/sec
500
300
100
0
700
720
710
t
Time period
Gigabytes/sec
1.8
1.5
1.0
0.5
0
720'
700'
710'
t
Time period

FIGURE 7

BANDWIDTH ALLOCATION OF BURSTY SIGNALS

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates generally to bandwidth allocation, and more particularly to a bandwidth enforcement policy that leverages a bursty characteristic of data transmission signals to efficiently utilize network resources.

2. Description of Related Art

Job control refers to the allocation of bandwidth to control multiple jobs accessing a network on a computer system. Proper enforcement of a bandwidth policy ensures that each job (or different tasks associated with each job) has access to adequate network resources to perform correctly.

Enforcing a network allocation policy is commonly performed by multitasking where more than one running program, or process, is present in the computer at any given time. If a process is unable to continue, its context can be stored and the computer can start or resume the execution of another process. Multitasking is usually performed by a scheduler that may interrupt and resume the execution of other processes. Typically, a driver for a peripheral device suspends execution of a current process if the device is unable to complete an operation immediately, and the scheduler places the process on its queue of sleeping jobs. The process is reawakened when the peripheral device can complete the operation. Similar suspension and resumption may also apply to inter-process communication, where processes communicate with one another in an asynchronous manner but may need to wait for a reply.

A process that seldom interacts with peripherals or other processes may dominate network resources until the process completes or is halted by manual intervention. The result is that the system is slow to react in a timely manner. This problem may be resolved by allocating each process a period of uninterrupted execution. The process may be assigned different priorities, and the scheduler may allocate varying shares of available execution time to each process on the basis of the assigned priorities. However, network resources may not be effectively utilized because many jobs and tasks do not transfer data at a constant rate or at predictable times.

BRIEF SUMMARY OF THE INVENTION

Aspects of the invention relate generally to bandwidth allocation by leveraging a bursty characteristic of data transmission signals to efficiently utilize network resources. The signals may be job signals to be executed by a network or task signals associated with the same job and also executed by the network. Network performance is observed over a time period to identify patterns of data transmission rates as the different signals are processed. The "burstiness" of signals is identified at different intervals in the time period. Burstiness refers to the characteristic of data signals where no data (or a relatively small amount of data) is transferred for an interval and then a significantly larger amount of data is suddenly transferred. The burstiness characteristic of signals is leveraged to allocate bandwidth such that network resources are efficiently utilized.

The bandwidth allocation is performed based on the observed behavior of the signals over the course of the time period. Bandwidth is initially allocated by dividing the peak bandwidth usage by the number of jobs or tasks. To compensate for the fact that different jobs/tasks peak at different times during the time period, a total bandwidth limit may be increased by a scaling factor. The scaling factor is calculated using information obtained by observing network performance during the time period. The scaling factor is then used to increase the total bandwidth available for all jobs/tasks executing during the time period without exceeding any bandwidth limits. The data transmission rate of each job/task may be adjusted to consume the newly available network bandwidth. In some cases, a bursty portion of the data transmission signal may be increased. In other cases, a non-bursty portion of the data transmission signal may be decreased. The different data transmission signals may also be assigned a priority value such that those signals having a higher priority are adjusted to consume the newly available network resources before those signals having a lower priority.

In some embodiments, a computer-implemented method includes observing execution of data transmission signals over a predetermined time period. At least some of the data transmission signals exhibit bursty characteristics. A peak bandwidth usage of all data transmission signals and a peak bandwidth demanded by each data transmission signal are identified during the time period. The peak bandwidth usage is divided by a total number of different data transmission signals that are executing during the time period. A total bandwidth demand scaling factor is calculated using a peak of the sum of bandwidth demands and a sum of the peak bandwidth demands for the data transmission signals. A total bandwidth limit for the data transmission signals is increased using the scaling factor.

In one aspect of the invention, a bandwidth limit is initially allocated for each data transmission signal using a quotient resulting from dividing the peak bandwidth usage by the total number of different data transmission signals. The initially allocated bandwidth limit is adjusted for each data transmission signal such that a total of the adjusted bandwidth limit for all of the data transmission signals does not exceed the increased total bandwidth limit.

In some embodiments, a computer-implemented method includes observing network execution of task signals over a predetermined time period. At least some of the task signals transmit data at varying rates during the time period. Each task signal is associated with a job signal and corresponds to an action performed on the network. The job signal corresponds to a portion of a program executing on the network. A total job bandwidth limit of all task signals, a peak bandwidth job usage of all task signals, and a peak bandwidth demanded are identified by each task signal during the time period. A bandwidth limit is initially allocated for each task signal by dividing the total job bandwidth limit by a total number of different task signals that are executing during the time period. A bandwidth job limit scaling factor is calculated using a peak of a sum bandwidth demands and a sum of the peak bandwidth demands for the task signals. The total bandwidth job limit is increased by the scaling factor. The initially allocated bandwidth limit is adjusted for each task signal such that a total of the adjusted bandwidth allocation limit for all of the task signals does not exceed the increased total bandwidth job limit.

In some embodiments, a computer-implemented method comprises observing network execution of job signals over a predetermined time period. At least some of the job signals transmit data at varying rates during the time period. Each job signal corresponds to a portion of a program executing on a network. A peak bandwidth usage of all job signals and a peak bandwidth demanded by each job signal are identified during the time period. A bandwidth limit is initially allocated to each job signal by dividing the peak bandwidth usage all job signals by a total number of different job signals that are executing during the time period. A total bandwidth demand scaling factor is allocated using a peak of a sum of bandwidth demands and a sum of the peak bandwidth demands for the job signals. A total bandwidth limit for the job signals is increased using the scaling factor. The initially allocated bandwidth limit is adjusted for each job signal such that the adjusted bandwidth limit for all of the job signals does not exceed the increased total bandwidth limit.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a functional diagram of a system in accordance with an aspect of the invention.

FIG. **2** is a pictorial diagram of the system of FIG. **1**.

FIG. **3** is an exemplary flow diagram in accordance with aspects of the invention.

FIG. **4** illustrates a graph of job signals before and after bandwidth is allocated in accordance with aspects of the invention.

FIG. **5** illustrates another graph of job signals before and after bandwidth is allocated in accordance with aspects of the invention.

FIG. **6** is an exemplary flow diagram in accordance with aspects of the invention.

FIG. **7** illustrates a graph of task signals before and after bandwidth is allocated in accordance with aspects of the invention.

DETAILED DESCRIPTION

As shown in FIGS. **1**-**2**, a system **100** in accordance with one aspect of the invention includes a computer **110** containing a processor **120**, memory **130** and other components typically present in general purpose computers.

The memory **130** stores information accessible by processor **120**, including instructions **132**, and data **134** that may be executed or otherwise used by the processor **120**. The memory **130** may be of any type capable of storing information accessible by the processor **120**, including a computer-readable medium, or other medium that stores data that may be read with the aid of an electronic device, such as a hard-drive, memory card, flash drive, ROM, RAM, DVD or other optical disks, as well as other write-capable and read-only memories. In that regard, memory may include short term or temporary storage as well as long term or persistent storage. Systems and methods employing aspects of the invention may include different combinations of the foregoing, whereby different portions of the instructions and data are stored on different types of media.

The instructions **132** may be any set of instructions to be executed directly (such as machine code) or indirectly (such as scripts) by the processor **120**. For example, the instructions may be stored as computer code on the computer-readable medium. In that regard, the terms “instructions” and “programs” may be used interchangeably herein. The instructions may be stored in object code format for direct processing by the processor **120**, or in any other computer language including scripts or collections of independent source code modules that are interpreted on demand or compiled in advance. Functions, methods and routines of the instructions are explained in more detail below.

The data **134** may be retrieved, stored or modified by processor **120** in accordance with the instructions **132**. For instance, although the architecture is not limited by any particular data structure, the data may be stored in computer registers, in a relational database as a table having a plurality of different fields and records, XML documents or flat files. The data may also be formatted in any computer-readable format.

The processor **120** may be any conventional processor, such as processors from Intel Corporation or Advanced Micro Devices. Alternatively, the processor **120** may be a dedicated controller such as an ASIC. Although FIG. **1** functionally illustrates the processor and memory as being within the same block, it will be understood by those of ordinary skill in the art that the processor and memory may actually comprise multiple processors and memories that may or may not be stored within the same physical housing. For example, memory may be a hard drive or other storage media located in a server farm of a data center. Accordingly, references to a processor or computer will be understood to include references to a collection of processors or computers or memories that may or may not operate in parallel.

The computer **110** may be at one node of a network **150** and capable of directly and indirectly receiving data from other nodes of the network. For example, computer **110** may comprise a web server that is capable of receiving data from client devices **160** and **170** via network **150** such that server **110** uses network **150** to transmit and display information to a user on display **165** of client device **170**. Server **110** may also comprise a plurality of computers that exchange information with different nodes of a network for the purpose of receiving, processing and transmitting data to the client devices. In this instance, the client devices will typically still be at different nodes of the network than any of the computers comprising server **110**.

Network **150**, and intervening nodes between server **110** and client devices, may comprise various configurations and use various protocols including the Internet, World Wide Web, intranets, virtual private networks, local Ethernet networks, private networks using communication protocols proprietary to one or more companies, cellular and wireless networks (e.g., WiFi), instant messaging, HTTP and SMTP, and various combinations of the foregoing. Although only a few computers are depicted in FIGS. **1**-**2**, it should be appreciated that a typical system can include a large number of connected computers.

Each client device **160** or **170** may be configured similarly to the server **110**, with a processor, memory and instructions as described above. Each client device **160** or **170** may be a personal computer intended for use by a person, and have all of the components normally used in connection with a personal computer such as a central processing unit (CPU) **162**, memory (e.g., RAM and internal hard drives) storing data **163** and instructions **164**, an electronic display **165** (e.g., a monitor having a screen, a touch-screen, a projector, a television, a computer printer or any other electrical device that is operable to display information), and user input **166** (e.g., a mouse, keyboard, touch-screen or microphone). The client device may also include a camera **167**, geographical position component **168**, accelerometer, speakers, a network interface device, a battery power supply **169** or other power source, and all of the components used for connecting these elements to one another.

Although the client devices **160** and **170** may each comprise a full-sized personal computer, they may alternatively comprise mobile devices capable of wirelessly exchanging data, including position information derived from position component **168**, with a server over a network such as the Internet. By way of example only, client device **160** may be a wireless-enabled PDA, a cellular phone, a tablet PC or a netbook capable of obtaining information via the Internet or other network. The user may input information, by way of example, using a small keyboard, a keypad or a touch screen.

Data **134** of server **110** may include may include task priority information **136** and job priority information **138**. A job may correspond to different parts of a program that are executing on the network **150**, while a task may correspond to a specific action that is performed by a job. Particular jobs and specific tasks within each job may take precedence over other jobs/tasks because the corresponding actions performed are considered to be of greater importance to the overall execution of the program than the actions performed by other jobs/tasks. Accordingly, the task priority information **136** identifies the priority of different tasks and the job priority information **138** identifies the priority of different jobs. As discussed in detail below, the jobs/tasks that are assigned with a higher priority may be performed before jobs/tasks with a lower priority, if possible.

In addition to the operations described below and illustrated in the figures, various operations in accordance with aspects of the invention will now be described. It should also be understood that the following operations do not have to be performed in the precise order described below. Rather, various steps can be handled in a different order or simultaneously.

FIG. **3** demonstrates a process **300** of allocating bandwidth among multiple jobs that are executing simultaneously using an algorithm. The process begins **300** when a network's performance is observed over a particular time period (step **310**). The time period may encompass any segment of time that is characteristic of network activity, for example, from less than one second up to several minutes or more. In one illustrative example, the time period is selected to be on the order of two minutes.

During the time period, the total number of jobs being executed by the network is identified (step **320**). Each job may correspond to different parts of the same program or to portions of different programs that are executing on the network. Example jobs include printing a file, saving a file to memory, and outputting a file to a display.

The peak bandwidth usage for all jobs is identified for the time period (step **330**). The peak bandwidth usage may not be the total amount of network bandwidth that is occupied by the jobs during the time period because most jobs are not constantly active for any given time period. In other words, some jobs may be executing while other jobs are waiting for the executing jobs to complete execution before the waiting jobs are initiated. This feature of limited data transmission followed by a sudden spike in high data transmission is, as explained above, commonly referred to as "burstiness". In one illustrative example, the total bandwidth available for all of the jobs executing during the time period (i.e., the total bandwidth demand) is 15 gigabytes per second, but the peak bandwidth usage for all of the jobs executing during the time period would most likely be less than 15 gigabytes per second. For example, the peak bandwidth usage for all of the jobs may be 10 gigabytes per second during the time period.

Bandwidth is initially allocated for each job by dividing the scaled-up total bandwidth limit for all jobs by the number of jobs executing during the time period (step **340**). In this case, each job is initially allocated substantially the same amount of bandwidth. Using a value of 10 gigabytes per second for the peak bandwidth usage for ten jobs executing during the time period, each job is allocated a bandwidth of 1 gigabyte per second to execute. Accordingly, 5 gigabytes per second of the total bandwidth remains unused during the time period.

This unused bandwidth can be leveraged against the bursty characteristic of at least some of the jobs in order to consume available network resources.

Any additional unused bandwidth of the total bandwidth may be allocated to the jobs such that the jobs may execute more efficiently. In one embodiment, each job may be assigned a substantially equal amount of unused bandwidth. However, since different jobs peak at different times, many of the jobs may not utilize a significant amount of the extra amount of bandwidth that is assigned to them. Accordingly, the equal allocation of the extra bandwidth may not be the most effective method of allocating network resources.

To compensate for the fact that different jobs will peak at different times during the time period, the total bandwidth limit may be increased by a scaling factor (k). The scaling factor may be computed in accordance with the following equation (step **350**):

$$k = \frac{\text{sum of peak bandwidth demands}}{\text{peak of sum of bandwidth demands}} \qquad \text{Eq. 1}$$

Assume that there are ten jobs executing during the time period, where two of the ten jobs demand a peak bandwidth of 1 gigabyte per second, three of the ten jobs demand a peak bandwidth of 2 gigabytes per second, and five of the ten jobs demand a peak bandwidth of 3 gigabytes per second. Also assume that the peak bandwidth usage for the time period is 10 gigabytes per second. In some embodiments, a peak of the sum of bandwidth demands may be approximated as slightly larger than a peak usage demand (i.e., 1.1×peak usage demand), and the sum of the peak of bandwidth demands is lightly larger than a sum of the peak of bandwidth usages (i.e., 1.1×sum of peak bandwidth usages). Based on these assumptions, the scaling factor is calculated to be:

$$k = \frac{1+1+2+2+2+3+3+3+3+3}{11} = \frac{23}{11} = 2.09 \qquad \text{Eq. 2}$$

The scaling factor is then used to increase the total bandwidth limit available for all of the jobs executing during the time period (step **360**). For example, if the total bandwidth demand is 15 gigabytes per second for the ten jobs during the time period, the total bandwidth demand is increased by the scaling factor of 2.09 to a value of 31.35 gigabytes per second. Increasing the total bandwidth limit by the scaling factor ensures that all jobs can be executed during the time period without adversely impacting the execution of any of the jobs due to unavailable network resources.

FIG. **4** illustrates a pair of graphs of two job signals before and after bandwidth is allocated by leveraging the burstiness characteristic of the signals to more efficiently utilize network resources. Referring to the upper graph, two different job signals **400**, **410** are illustrated. Each signal **400**, **410** transmits data at a high rate for a time interval and then transmits data at a relatively lower rate (or not at all) during a different time interval. In some cases, the burstiness of the signals **400**, **410** may be because data could not be transmitted due to insufficient network bandwidth. In other cases, the burstiness of the signals **400**, **410** may be because data could not be transmitted until another job completed execution.

As shown in the upper graph, job signal **400** begins at time t=0 at a data transmission rate that is zero gigabytes per second. The rate at which signal **400** is transmitting data increases until 3 gigabytes per second is reached. This rate is maintained for an interval before the data transmission rate decreases to zero. No data is transmitted by job signal **400** for an interval before transmission resumes as in the previous transmission interval. The job signal **400** continues to exhibit these bursty characteristics in a cycle until the time period elapses.

Similarly, job signal **410** begins at time t=0 at a data transmission rate of 1 gigabyte per second. The rate at which signal **410** is transmitting data is maintained for an interval before the data transmission rate increases to a rate of 5 gigabytes per second. This rate is maintained for an interval before the data transmission rate decreases to 1 gigabyte per second. The job signal **410** continues to exhibit this cyclical bursty characteristic until the time period elapses.

In accordance with embodiments of the invention, the bursty characteristic of the signals **400**, **410** may be leveraged to increase the efficiency of network resources using the process described with reference to FIG. **3**. The peak bandwidth usage for job signal **400** is 3 gigabytes per second and the peak bandwidth usage for job signal **410** is 5 gigabytes per second. When job signal **400** is transmitting data at 3 gigabytes per second, job signal **410** is transmitting data at 1 gigabyte per second. In other words, the peak bandwidth usage during this time interval is 4 gigabytes per second. Accordingly, the peak bandwidth usage for all jobs that are executing during the total time period is 5 gigabytes per second, and the sum of peak bandwidth demand for all jobs is 8 gigabytes per second (i.e., 5 gigabytes per second+3 gigabytes per second=8 gigabytes per second). The peak of the sum of bandwidth demands may be calculated by multiplying the peak bandwidth usage of 5 gigabytes per second by 1.1 to obtain a value of 5.5. Thus, the scaling factor is equal to 8/5 or 1.6.

As shown in the figure, the total bandwidth demand is 5 gigabytes per second. This is the maximum amount of bandwidth that is required at any given time during the time period. The total bandwidth demand value is multiplied by the scaling factor to determine a new value for the total bandwidth demand. In other words, the new value for the total bandwidth demand becomes 1.45×5 or 7.25 gigabytes per second for all jobs executing during the time period.

Referring to the lower graph in FIG. **4**, the data transmission rate of signal **410** can be increased up to 7.25 gigabytes per second (see signal **410'**) when a data burst is transmitted. When transmitting at the new total bandwidth demand value, data transmission is not adversely affected because the only other job (i.e., signal **400**) is not transmitting any data during the same interval.

In some embodiments, as shown in the lower graph, signal **410** may not be increased for the portions that do not exhibit bursty characteristics. For example, the lowest rate at which job signal **410** transmits data is 1 gigabyte per second. When the bursty portion of signal **410** is increased to form signal **410'**, the low data transmission rate may be maintained at 1 gigabyte per second.

In other embodiments, signal **410** may be decreased for the portions that do not exhibit bursty characteristics. For example, the lowest rate at which job signal **410** transmits data is 1 gigabyte per second. When the bursty portion of signal **410** is increased to form signal **410'**, the low data rate may be reduced down to zero gigabytes per second (see signal **410"** in FIG. **5**). In this case, data that was transmitted during the 1 gigabyte per second transfer rate of signal **410** may be prevented from being transmitted until the bursty portion of signal **410"** is used to transmit the data.

The data transmission rate of the bursty portion of signal **400** may also be increased without interfering with the execution of other jobs on the network (i.e., because the signal **410'** does not exhibit bursty characteristics during the same interval.) For example, in the event that the non-bursty portion of signal **400'** remains at 1 gigabyte per second, the bursty portion of signal **400** may be increased up to 6.25 gigabytes per second (see signal **400'**).

The data transmission rate of a signal that is exhibiting burstiness may be further increased by decreasing the data transmission rate of a signal that is not exhibiting bursty characteristics during the same interval. Signal **400** may be increased more than signal **400'** if the non-bursty portion of signal **410** is reduced as long as the two signals together do not exceed the new value for the total bandwidth limit. In other words, the data transmission rate of signal **400** can be increased when a data burst is transmitted without adversely affecting network performance because the non-bursty portion of signal **410** is utilizing less network bandwidth.

As illustrated in FIG. **5**, signal **400** may be increased up to 7.25 gigabytes per second (as indicated by signal **400"**) if signal **410** is reduced to zero gigabytes per second (as indicated by signal **410"**) during the same time interval. Accordingly, a data transmission rate may be increased when a signal exhibits burstiness and decreased when a signal does not exhibit burstiness in order to provide for the efficient utilization of available network bandwidth.

In the examples described above with reference to FIGS. **4**-**5**, two data transmission signals are described. However, it is understood that more than two signals would commonly be executing simultaneously. In these cases, the signals may be prioritized to identify which signals should be addressed first to increase the data transmission rates of the higher priority signals, before adjusting the data transmission rates of lower priority signals. The concept of prioritization is discussed in detail below with reference to FIG. **7**.

FIG. **6** demonstrates a process **600** using an algorithm to allocate bandwidth among multiple, simultaneously executing tasks of a particular job. Process **600** is similar to process **300**, but process **300** is directed to job signals while process **600** is directed to task signals. A task commonly refers to a single computation or action performed on a network. Many tasks may comprise a single job. For example, one task may be to retrieve a data value, another task may be to perform an operation on the value, and still another task may be to output the value to another job. In another example, one task may be to continually increment a data value as a function of time, another task may be to determine whether a data value exceeds a threshold, still another task may be to perform an action on the value, and yet another task may be to store the value in memory.

The process begins **600** when network performance is observed over a particular time period (step **610**). The time period may encompass any segment of time that is characteristic of network activity. The time period may be the same observation period discussed above with reference to FIG. **3** (e.g., on the order of two minutes or some other time period).

In one illustrative example, hundreds of tasks are executing on the same network. However, most of the tasks are not constantly transferring data. For example, one task may not transfer any data for a few seconds but may then suddenly transmit 1 gigabyte of data during the next second and then not transmit any data thereafter for another few seconds. As discussed above, this type of sudden high data transmission rate preceded or followed by little or no data transmission is referred to as “burstiness”. The burstiness of a data transmission signal may be leveraged to increase effective network bandwidth allocation.

During the time period, the total number of tasks being executed by the network is identified for a particular job (step **620**). As stated, there may be hundreds of tasks executing for any given job. However, for ease of description, the number of tasks for process **600** is identified as five.

The peak bandwidth limit allocated for the job that performs the tasks (i.e., the "job bandwidth limit") is identified for the time period (step **630**). The job bandwidth limit may be the scaled bandwidth for the job as described with reference to step **360** in FIGS. **4-5**. In one illustrative example, a job bandwidth limit may be 5 gigabytes per second.

Bandwidth is initially allocated for each task by dividing the job bandwidth limit by the number of tasks for the job executing during the time period (step **640**). In this case, each task is initially allocated substantially the same amount of bandwidth. Using the values of five tasks executing during the time period and a job bandwidth limit of 5 gigabytes per second, each task is allocated a bandwidth of 1 gigabyte per second.

Since most task signals do not transmit data at a constant rate, the job bandwidth limit will not be completely utilized during the time period. Any unused bandwidth may be allocated to the tasks such that the tasks may have more network resources available in which to execute more effectively. Specifically, the unused bandwidth can be leveraged against the bursty characteristic of at least some of the tasks in order to consume the unused bandwidth.

To compensate for the fact that different tasks will peak at different times during the time period, the job bandwidth limit may be increased by a scaling factor (k). The scaling factor may be computed in accordance with the following equation (step **650**):

$$k = \frac{\text{sum of peak bandwidth demands}}{\text{peak of sum of demands}} \qquad \text{Eq. 3}$$

In the illustrative example, five tasks are executing during the time period, where two of the tasks demand a peak bandwidth of 250 megabytes per second and three of the tasks demand a peak bandwidth of 500 megabytes per second. Also, the peak of the sum of demands for the time period may be calculated by multiplying the peak job usage of 1 gigabyte per second for the time period by a number slightly larger than 1 (e.g., 1.1). In this case, a value of 1.1 gigabytes per second is obtained. Based on these values, the scaling factor is calculated to be:

$$k = \frac{.25 + .25 + .5 + .5 + .5}{1.1} = \frac{2}{1.1} = 1.81 \qquad \text{Eq. 4}$$

The scaling factor is then used to increase the job bandwidth limit available for all of the tasks executing during the time period (step **660**). For example, if the job bandwidth limit is 1.25 gigabytes per second for the five tasks during the time period, the job bandwidth limit is increased by the scaling factor of 1.81 to a value of 2.26 gigabytes per second. Increasing the job bandwidth limit by the scaling factor ensures that all tasks can be executed during the time period while efficiently using available network resources without adversely impacting the execution of any of the tasks.

The bandwidth limit of each task is then adjusted such that the total adjusted bandwidth for all of the tasks does not exceed the scaled job bandwidth limit (step **670**). Each of the five tasks was initially allocated a bandwidth of 1 gigabyte per second in step **640**. This value is adjusted for each task such that a larger portion of the increased job bandwidth limit may be utilized. In one example, the data transmission rate of each task may be increased by the same amount until all of the increased job bandwidth is utilized. In another example, each task may be assigned a priority value, and the tasks with higher priority values may have their data transmission rates increased before those with lower priority values until all of the increased job bandwidth is utilized. In another example, the tasks with lower priority values may have their data transmission rates decreased such that the tasks with higher priority values may have their data transmission rates further increased.

FIG. **7** illustrates graphs of three task signals before and after bandwidth is allocated to leverage the burstiness characteristic of the signals to more efficiently utilize network resources. For purposes of discussion, a job includes different tasks as illustrated by task signals **700**, **710**, **720**. As shown in the upper graph, task signal **700** begins at time t=0 at a data transmission rate of 100 megabytes per second. The rate at which signal **700** is transmitting data increases until a rate of 500 megabytes per second is reached. This rate is maintained for an interval before the data transmission rate decreases to 100 megabytes per second. The task signal **700** continues to exhibit these bursty characteristics until the time period elapses.

Similarly, task signal **710** begins at time t=0 at a data transmission rate of 25 megabytes per second. As shown in the graph, the rate at which signal **710** is transmitting data is maintained for an interval before the data transmission rate increases to a rate of 300 megabytes per second. This rate is maintained for an interval before the data transmission rate decreases to 25 megabytes per second. The task signal **710** continues to exhibit this cyclical bursty characteristic until the time period elapses.

Task signal **720** begins at time t=0 at a data transmission rate of 350 megabytes per second. As shown in the graph, the rate at which signal **720** is transmitting data is maintained for an interval before the data transmission rate decreases to a rate of 150 megabytes per second. This rate is maintained for an interval before the data transmission rate increases to 350 megabytes per second. The task signal **720** continues to exhibit these cyclical features until the time period elapses.

The peak bandwidth usage for task signal **700** is 500 megabytes per second, the peak bandwidth usage for task signal **710** is 300 megabytes per second and the peak bandwidth usage for task signal **720** is 350 megabytes per second. When task signal **700** is transmitting data at 500 megabytes per second, task signal **710** is transmitting data at 25 megabytes per second and task signal **720** is transmitting data at a rate of between 150-350 megabytes per second. In other words, the peak bandwidth usage for the job during this time interval is 875 megabytes per second.

In accordance with embodiments of the invention, the bursty characteristic of task signals **700**, **710**, **720** may be leveraged to increase the efficiency of network resources using the process described with reference to FIG. **6**. For purposes of discussion, the task signals **700**, **710**, **720** are executed during the processing of a job signal that has a peak bandwidth allocation value of 1.5 gigabytes per second with a peak job usage of 875 megabytes per second (as identified above with reference to signals **700**, **710**, **720**). The peak bandwidth allocation value is divided by the number of tasks associated with the job (here, three) to provide the initial bandwidth value that is allocated to each task. In other words, each task signal **700**, **710**, **720** is initially allocated bandwidth of 0.5 gigabytes per second.

The job bandwidth limit scaling factor is calculated using Equation 3. The sum of the peak bandwidth demand for all tasks is equal to 500+300+350=1150 megabytes per second=1.15 gigabytes per second. The peak of the sum of bandwidth demands is slightly larger than peak job usage such that the peak of the sum of bandwidth demands may be 1.1× 875=962 megabytes per second=0.96 gigabytes per second. Accordingly, the scaling factor is equal to 1.15/0.96 or 1.2.

The scaling factor value k=1.2 is used to increase the total job bandwidth limit. As stated above, the total job bandwidth limit is 1.5 gigabytes per second. Accordingly, this limit is increased using the scaling factor to 1.8 gigabytes per second.

The data transmission rate of each task signal is adjusted such that the scaled total job bandwidth limit is not exceeded. In other words, the data transmission rate of all of the tasks cannot exceed 1.8 gigabytes per second. Each task signal **700**, **710**, **720** was initially allocated the same amount of bandwidth (0.5 gigabytes per second). This value may be adjusted up or down to any value as long as the total data transmission rate for all tasks does not exceed 1.8 gigabytes per second.

In one embodiment, the data transmission rate of each task is increased by the same amount until all of the job bandwidth is utilized. In other embodiments, as discussed below, each task may be assigned a priority value, and the tasks with higher priority values may have their data transmission rates increased before those with lower priority values until all of the job bandwidth is utilized. Alternatively or additionally, the tasks with lower priority values may have their data transmission rates decreased such that the tasks with higher priority values may have their data transmission rates further increased.

As stated, the different task signals that are executing simultaneously and vying for network resources may each be provided a priority such that the data transmission rates may be altered based on the priority. In one case, certain types of data transmission signals may be assigned a higher priority than other signals because the data that they are transmitting or receiving is deemed to be of greater importance. This priority assignment may be performed at the design stage such that the network automatically identifies the priority. In another case, the characteristics of the data transmission signal itself determine its priority. For example, a signal that generally exhibits higher data transmission rates may be automatically assigned a higher priority than a signal that generally transfers data at lower rates. For ease of description, we assume that signal **700** has a higher priority than signal **710**, and that signal **710** has a higher priority than signal **720**.

Referring to the lower graph of FIG. **7**, the total job bandwidth limit is 1.8 gigabytes per second. The task signals **700**, **710**, **720** can be adjusted in any number of ways to utilize the newly available bandwidth more effectively. For example, task signal **700** may be increased to 1.5 gigabytes per second resulting in adjusted task signal **700'**. In addition, the bursty portion of task signal **710** (having the second highest priority) may also be increased to 1.5 gigabytes per second while the non-bursty portion of task signal **710** may be decreased to a value of zero, resulting in adjusted task signal **710'**. Lastly, task signal **720** (having the lowest priority) may be adjusted to utilize any remaining available job bandwidth limit. One way to achieve this may be to increase the bursty portion of task signal **720** to 1.5 gigabytes per second while decreasing the non-bursty portion of task signal **720** to a value of zero, resulting in adjusted task signal **720'**.

The adjusted task signals **700'**, **710'**, **720'** all have a maximum data transmission of 1.5 gigabytes per second. This feature may be beneficial in some cases; however, other cases may warrant that the higher priority signals transmit data at a higher maximum rate than lower priority signals.

As described above, bandwidth is allocated by leveraging a bursty characteristic of data transmission signals to efficiently utilize network resources. Network performance is observed over a time period to identify patterns of data transmission rates as the different signals are processed. The bandwidth allocation is performed based on the observed behavior of the signals over the course of the time period. To compensate for the fact that different jobs/tasks peak at different times during the time period, the total bandwidth limit may be increased by a scaling factor. The scaling factor is calculated using information obtained by observing network performance during the time period. The scaling factor is then used to increase the total bandwidth available for all jobs/tasks executing during the time period without exceeding any bandwidth limits. The data transmission rate of each job/task may then be adjusted to utilize the newly available bandwidth.

As these and other variations and combinations of the features discussed above can be utilized without departing from the invention as defined by the claims, the foregoing description of exemplary embodiments should be taken by way of illustration rather than by way of limitation of the invention as defined by the claims. It will also be understood that the provision of examples of the invention (as well as clauses phrased as "such as," "e.g.", "including" and the like) should not be interpreted as limiting the invention to the specific examples; rather, the examples are intended to illustrate only some of many possible aspects.

The invention claimed is:

1. A computer-implemented method comprising:

observing, by a processor, execution of data transmission signals over a predetermined time period, wherein at least some of the data transmission signals exhibit bursty characteristics;

identifying a peak bandwidth usage of all data transmission signals and a peak bandwidth demanded by each data transmission signal during the time period;

dividing the peak bandwidth usage by a total number of different data transmission signals that are executing during the time period;

calculating a total bandwidth demand scaling factor (k) using a peak (U) of the sum of bandwidth demands and a sum (P) of the peak bandwidth demands for the data transmission signals, wherein the scaling factor (k) is calculated according to the equation

$$k = \frac{P}{U},$$

and where P>U; and

increasing, using the processor, a total bandwidth limit for the data transmission signals using the scaling factor.

2. The method of claim **1**, wherein the data transmission signals are job signals, each job signal corresponding to a portion of a program executing on a network.

3. The method of claim **1**, wherein the data transmission signals are task signals associated with a job signal, each task signal corresponding to an action performed on a network.

4. The method of claim **1**, further comprising:

initially allocating a bandwidth limit for each data transmission signal using a quotient resulting from dividing the peak bandwidth usage by the total number of different data transmission signals; and adjusting the initially allocated bandwidth limit for each data transmission signal, wherein a total of the adjusted bandwidth limit for all of the data transmission signals does not exceed the increased total bandwidth limit.

5. The method of claim **4**, wherein the adjusting further comprises:

increasing a bursty portion of at least some of the data transmission signals.

6. The method of claim **5**, wherein each data transmission signal is associated with a priority value, and the adjusting further comprises:

increasing the bursty portion of a first one of the data transmission signals having a higher priority value before increasing the bursty portion of a second one of the data transmission signals having a lower priority value.

7. The method of claim **5**, wherein the adjusting further comprises:

decreasing a non-bursty portion of at least some of the data transmission signals.

8. The method of claim **7**, wherein each data transmission signal is associated with a priority value, and the adjusting further comprises:

decreasing the non-bursty portion of a first one of the data transmission signals having a lower priority value before decreasing the non-bursty portion of a second one of the data transmission signals having a higher priority value.

9. A computer-implemented method comprising:

observing network execution of task signals over a predetermined time period, wherein at least some of the task signals transmit data at varying rates during the time period, each task signal being associated with a job signal and corresponding to an action performed on the network, wherein the job signal corresponds to a portion of a program executing on the network;

identifying a total job bandwidth limit of all task signals, a peak bandwidth job usage of all task signals, and a peak bandwidth demanded by each task signal during the time period;

initially allocating a bandwidth limit for each task signal by dividing the total job bandwidth limit by a total number of different task signals that are executing during the time period;

calculating a bandwidth job limit scaling factor (k) using a peak (U) of the sum of bandwidth demands and a sum (P) of the peak bandwidth demands for the task signals, wherein the scaling factor (k) is calculated according to the equation

$$k = \frac{P}{U},$$

and where P>U;

increasing the total bandwidth job limit by the scaling factor; and

adjusting the initially allocated bandwidth limit for each task signal, wherein a total of the adjusted bandwidth allocation limit for all of the task signals does not exceed the increased total bandwidth job limit.

10. The method of claim **9**, wherein the adjusting further comprises:

increasing a bursty portion of at least some of the task signals.

11. The method of claim **10**, wherein each task signal is associated with a priority value, and the adjusting further comprises:

increasing the bursty portion of a first one of the task signals having a higher priority value before increasing the bursty portion of a second one of the task signals having a lower priority value.

12. The method of claim **10**, wherein the adjusting further comprises:

decreasing a non-bursty portion of at least some of the task signals.

13. The method of claim **12**, wherein each task signal is associated with a priority value, and the adjusting further comprises:

decreasing the non-bursty portion of a first one of the task signals having a lower priority value before decreasing the non-bursty portion of a second one of the task signals having a higher priority value.

14. A computer-implemented method comprising:

observing network execution of job signals over a predetermined time period, wherein at least some of the job signals transmit data at varying rates during the time period, each job signal corresponding to a portion of a program executing on a network;

identifying a peak bandwidth usage of all job signals and a peak bandwidth demanded by each job signal during the time period;

initially allocating a bandwidth limit to each job signal by dividing the peak bandwidth usage all job signals by a total number of different job signals that are executing during the time period;

calculating a total bandwidth demand scaling factor (k) using a peak (U) of the sum of bandwidth demands and a sum (P) of the peak bandwidth demands for the job signals, wherein the scaling factor (k) is calculated according to the equation

$$k = \frac{P}{U},$$

and where P>U;

increasing a total bandwidth limit for the job signals using the scaling factor; and

adjusting the initially allocated bandwidth limit for each job signal, wherein the adjusted bandwidth limit for all of the job signals does not exceed the increased total bandwidth limit.

15. The method of claim **14**, wherein the adjusting further comprises:

increasing a bursty portion of at least some of the job signals.

16. The method of claim **15**, wherein each job signal is associated with a priority value, and the adjusting further comprises:

increasing the bursty portion of a first one of the job signals having a higher priority value before increasing the bursty portion of a second one of the job signals having a lower priority value.

17. The method of claim **15**, wherein the adjusting further comprises:

decreasing a non-bursty portion of at least some of the job signals.

18. The method of claim **17**, wherein each job signal is associated with a priority value, and the adjusting further comprises:

decreasing the non-bursty portion of a first one of the job signals having a lower priority value before decreasing a non-bursty portion of a second one of the job signals having a higher priority value.

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